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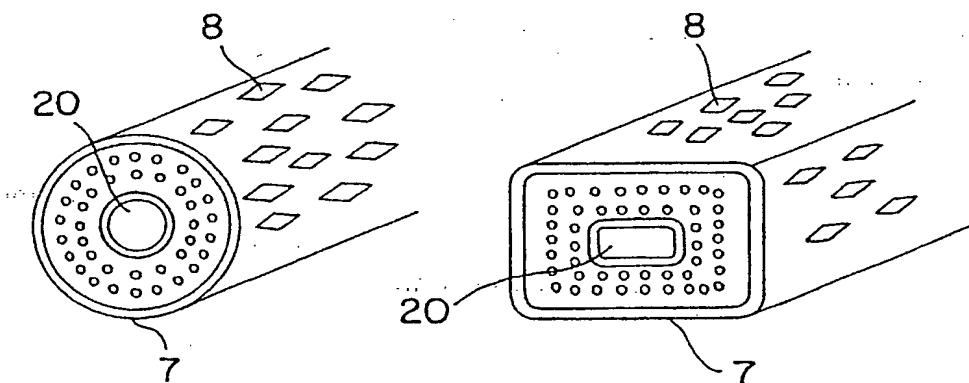
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(54) Title: CONSTRAINED FILAMENT NIOBIUM-BASED SUPERCONDUCTOR COMPOSITE AND PROCESS OF FABRICATION



(57) Abstract: A niobium-based superconductor is manufactured by establishing multiple niobium components in a billet of a ductile metal, working the composite billet through a series of reduction steps to form the niobium components into elongated elements, each niobium element having a thickness on the order of 1 to 25 microns, surrounding the billet prior to the last reduction step with a porous confining layer of an acid resistant metal, immersing the confined billet in an acid to remove the ductile metal from between the niobium elements while the niobium elements remain confined by said porous layer, exposing the confined mass of niobium elements to a material capable of reacting with Nb to form a superconductor.

1 CONSTRAINED FILAMENT NIOBium-BASED SUPERCONDUCTOR COMPOSITE
2 AND PROCESS OF FABRICATION
3

4 The present invention pertains to the fabrication of A-15 type
5 multifilament composite superconductors (By "A-15" is meant the inter
6 metallic compounds having β W structure). These include Nb₃Sn, and Nb₃Al
7 and are important because of their superior high field properties.
8 Unfortunately, they are brittle compounds, difficult to make as fine filaments
9 and as a result are very expensive. For these reasons, the ductile NbTi
10 superconductors has dominated the commercial market even though its
11 maximum magnetic field are limited to less than 8 Tesla. Significant
12 improvements are needed in order to commercialize the A-15 conductors and
13 to extend the useful magnetic fields to the 12 Tesla range on a cost effective
14 basis. The present invention is also applicable to the production of the "B1"
15 superconductors NbN and NbC.

16 A detailed description of present day methods currently being used in
17 the industry is described in an article entitled "A-15 Superconductors" in the
18 Metals Handbook, Tenth Edition, Volume 2 on pages 1060-1077, authored by
19 David B. Smathers. Two processes are currently being used. One employs a pure
20 bronze alloy as the matrix, the other a combination of pure copper and a pure
21 Sn core. The first is known as the "Bronze Process" and the latter the
22 "Internal Tin Process". The bronze matrix contains up to 13% Sn work
23 hardens rapidly and requires frequent annealing steps. These anneals are
24 avoided with the internal tin process. However, the cold drawing in the
25 Internal Tin process can result in poor bonding, degraded filament quality
26 and poor yields. After final drawing and twisting, both types of conductors
27 are heated to approximately 700°C for 200 hours or more to form Nb₃Sn.
28 Magnets are made exclusively by the Wind and React method.

29 The current densities that are obtained are substantially below what is
30 theoretically possible based on experimental short sample data. Contributing

1 to this problem is the low reaction temp of up to 700°C, requiring hundreds of
2 hours of reaction heat treatment. As the Sn is depleted, the Sn gradient is
3 reduced which further limits the reaction. Unreacted Nb in the Nb filament
4 can be left and Kirkendall type voids are formed in the residual matrix
5 resulting in a lowering of the current density and mechanical properties of the
6 conductor.

7 Significant improvements are needed to improve the high field
8 performance and to reduce the cost of these important A-15 conductors.

9 In the fabrication of Nb₃Sn superconducting wire, a barrier, usually
10 tantalum or a tantalum alloy is employed to prevent tin contamination of the
11 stabilizing copper on the exterior of the wire during heat treatment. The
12 process is described in the article by David B. Smathers. While the porous
13 metal sheath described in the present invention is similar to the barrier used
14 in Nb₃Sn conductor fabrication, application of the technology in this invention
15 is entirely unique.

16 US Patent Nos. 5,034,857 and 5,869,196 by Wong, discloses a novel
17 approach to the production of very fine valve metal filaments, preferable
18 tantalum, for capacitor use. The benefits of fine filaments relative to fine
19 powders are higher purity, lower cost, uniformity of cross section, and ease of
20 dielectric infiltration, while still maintaining high surface area for
21 anodization. The uniformity of cross section results in capacitors with high
22 specific capacitance, lower ESR and ESL, and less sensitivity to forming
23 voltage and sintering temperature as compared to fine powder compacts.
24 Other patents involving valve metal filaments and fibers, their fabrication, or
25 articles made therefrom include US Patent Nos. 3,277,564 (Webber), 3,379,000
26 (Webber), 3,394,213 (Roberts), 3,567,407 (Yoblin), 3,698,863 (Roberts) 3,742,369
27 (Douglass), 4,502,884 (Fife), 5,306,462 (Fife) and 5,245,514 (Fife).

28 The prior art relating to the fabrication of A-15 conductors can be
29 obtained by reading both Smather's article and "Filamentary A-15
30 Superconductors" by Masaki Suenaga and Alan F. Clark, Plenum Press, N.Y.

1 Cryogenic Material Series (published 1980). In this book, the article by C.H.
2 Rosner, B.A. Zeitlin, R.CX. Schwall, M.S. Walker and G.M. Ozeryansky
3 entitled "Review of Superconducting Activities at IGC on A-15 Conductors"
4 pages 67-79, specifically summarizes the earlier developments. Initially,
5 powder metallurgy methods were employed followed soon by surface
6 diffusion of liquid Sn of both Nb tapes and wires. Allen 3,218,693 patented a
7 method where Sn coated Nb ribbons and wire were reacted to form Nb₃Sn at
8 temperatures between 800°C to 1000°C. Similar products were also made by
9 General Electric and later by IGC. The Nb wires in cable form, were Sn
10 dipped, wound into a magnet and reacted; D.F. Martin et al Patent No.
11 3,429,032. A subsequent article, by Scanlan and Fietz, "MultiFilamentary
12 Nb₃Sn for Superconducting Generator application", IEEE Trans. MAG-11
13 page 287, March '75, describes fabrication of a Nb₃Sn cable employing
14 electroplated Sn as the Sn source.

15 A new approach is necessary to improve the processing of Nb₃Sn
16 conductors. In the early 1960's, pure Nb tapes, wires and cable were dipped
17 in molten Sn baths which was then reacted at high temperatures to form
18 Nb₃Sn. Because Nb₃Sn is brittle, a ductile substrate of unreacted Nb was left
19 to permit handling and subsequent winding into magnets. However, the
20 need for stable, fine filaments and twisted conductors soon made this method
21 obsolete.

22 Wong's patent '196 describes a process used to manufacture Ta
23 capacitors where Ta multifilaments are made in a constraining sheath. This
24 process describes the removal of the copper matrix after the final forming
25 operation. The advantages of the external sheath is that final packaging of the
26 filaments are unnecessary since the filaments are now constrained and
27 supported by the outer sheath. Furthermore, the area inside the sheath is
28 exactly determined as is the volume fraction of Ta.

29 A precursor wire, containing fine Nb filaments enclosed in a
30 constraining sheath which can act as a supporting structure is produced.

1 Upon the removal of the copper matrix, and employing a liquid Sn dipping
2 process, Sn or a CuSn alloy is used to infiltrate and surround the Nb
3 filaments. The significant advantage here is that the need for subsequent wire
4 drawing is completely eliminated as is the co-processing and low yield
5 difficulties of present day Nb₃Sn conductors. The ability to easily increase the
6 Sn concentration can result in substantial improvement in current density
7 over present day conductors. The sheath, in the preferred embodiments, is
8 made of Nb although Ta and stainless steel could also be used. The sheath is
9 fabricated by methods as described in US Patent No. 5,869,196 by Wong. The
10 billet is processed in the normal manner by extrusion and wire drawing to the
11 final size. The copper matrix is then removed from this precursor wire and
12 replaced with a Sn or CuSn alloy matrix. Final reaction heat treatments are
13 then used to convert the Nb to Nb₃Sn.

14 Fig. 1 is a schematic depiction of the primary billet used in the present
15 invention, Fig. 1a showing a transverse cross section, and Fig. 1b showing a
16 cutaway view revealing the longitudinal disposition of the billet components.

17 Fig. 2 is a schematic depiction of the transverse cross section of the
18 secondary billet used in the process of the present invention.

19 Fig. 3 is a schematic depiction of the product of the preferred
20 embodiment of the present invention, Fig. 3a showing the product as a
21 cylindrical body, and Fig. 3b showing the product after shaping into a
22 rectangular body.

23 Fig. 4 is similar to Fig. 3 but shows the internal copper core to achieve
24 stabilization.

25 Figs. 5-9 show additional systems for constraining the niobium
26 filaments during and after the step of acid leaching of the copper.

27 Fig. 10 is a schematic depiction of the primary billet used in the
28 preferred embodiment of the present invention.

29 This invention is directed to the fabrication of the fine metal filaments
30 for use as the base for reaction with tin (for example) to produce A-15

1 superconductors in situ. A very small body of constrained filaments and a
2 method for manufacture are disclosed. The invention will be of greatest value
3 in the superconductor industry, which seeks to develop increasingly high
4 magnetic field A-15 superconductors. The metal is selected from among the
5 metallic elements, niobium and in particular, the A-15 compounds of Nb. In a
6 preferred form, the product of the present invention, the metal filaments are
7 of a diameter less than 50 microns. They are constrained within a cylindrical
8 sheath, also made of metal, which has a wall thickness of 100 microns or less.
9 The metal that forms the sheath is preferably the same as that of the filaments,
10 but it is not necessarily so; tantalum can be used as well as stainless steel.
11 Multifilament conductors suitable for use as superconductors are formed
12 through the reduction of a metal billet consisting of multiple filaments of an
13 appropriate refractory metal, preferably niobium, contained within, and
14 spaced apart by, a ductile metal, preferably copper. The Nb filaments are
15 elongated and substantially parallel within the billet as shown in Fig. 2. The
16 array of Nb filaments 4 within the billet is surrounded by a confining layer of
17 metal 7. This metal 7 is preferably, but not necessarily, the same as that which
18 forms the filaments. The metal layer 7 preferably completely surrounds the
19 Nb filament array 4 circumferentially and runs the full length of the filaments.
20 The layer is separated from the filament array 4 by the same ductile metal 6
21 (e.g. Cu) that serves to separate the filaments 4 from each other. This same
22 ductile metal 6 can also form the surface of the billet, preventing exposure of
23 the confining metal layer during heating etc. The billet is reduced by
24 conventional means, such as extrusion and wire drawing. The confining
25 metal sheath 7 is then perforated (as shown in Figs. 3a and 3b at 8) such that
26 the mineral acid can readily diffuse through the porous layer and remove the
27 ductile copper separating the Nb filaments. It is important that these
28 perforations 8 should be designed such that the sheath retains its ability to
29 restrain and support the loose Nb filaments 4. More importantly, they should
30 not substantially weaken the strength or ductility of the entire composite.

1 Preferably, the perforation 8 can be accomplished by mechanically rolling the
2 wire in a rolling mill with the desired perforation pattern in a continuous
3 matter. Other means can be also employed, such as selective chemical
4 etching, laser drilling, etc. as would be apparent to one skilled in the art. The
5 constraining metal must be one that is inert to the acid used to dissolve the
6 copper.

7 Typical shapes would be a circular Fig. 3a or rectangular cross section
8 Fig. 3b. An advantage for the rectangular shape is that the distance for the
9 acid to penetrate for complete copper removal is reduced. Internal copper
10 stabilization can be introduced as shown in Fig. 4. The Ta clad copper
11 appears as a central core with a Ta diffusion barrier layer and it also reduces
12 the leaching time. Thereafter, the copper-free confined bundle of Nb
13 filaments is infiltrated with liquid Sn or CuSn alloy to thoroughly coat and
14 embed each Nb filament in a solid Sn or CuSn alloy matrix. The Sn is then
15 reacted with Nb to form Nb₃Sn in a separate step. Temperatures between
16 700°C to 1100°C are used, both performed in an inert atmosphere or vacuum
17 chamber. The Nb-filaments may be reacted partially, completely or it can be
18 completed at a later stage in the manufacture, e.g. after cabling or winding in
19 a magnet.

20 In one preferred form of the invention, the Nb filaments, at the
21 completion of the mechanical reduction step, will have a diameter on the
22 order of one to twenty-five microns. In this preferred final form of the
23 composite, the Nb filaments are separated by the Cu matrix and the Nb-Cu
24 structure is surrounded by a 50 micron or less thick layer of Nb having an
25 effective porosity of 50% or less. When this composite is immersed in an acid
26 leaching bath of HNO₃ and H₂O at 100°C, the copper is removed in about 60
27 min, leaving a bundle of micron size Nb filaments confined by a porous Nb
28 sheath. When this copper-free mass of Nb filaments is immersed in a Sn alloy
29 bath between 700°C to 1100°C the surface tension of the molten Sn bath and
30 the capillarity of the bundle of Nb filaments enclosed within the sheath draws

1 the tin into the bundle where it completely surrounds each Nb filament. The
2 Sn is then reacted with the Nb to form the Nb₃Sn compound at a later stage of
3 manufacturing.

4 As will be apparent to one skilled in the field of metallurgy, this
5 porosity can be achieved, for example, by mechanically perforating the
6 confining layer wherein the perforations 8 are uniformly spaced about 0.25
7 mm apart with a diamond shape size of 0.13 mm x 0.25 mm, as shown in Figs.
8 3a and 3b.

9 When the acid leaching of the copper from the Nb-Cu matrix results in
10 unacceptably high amounts of surface contamination on the Nb filaments,
11 these contaminates can be removed by the techniques described on page 9,
12 lines 38-55, in my earlier patent 5,869,169. Such deoxidation treatments may
13 improve the wetting of the Nb filaments by the liquid Sn alloy as well.

14 Prior to copper removal, multiple strands of wire can be cabled
15 together and compacted if required. This would avoid any mechanical
16 damage to the Nb filaments because, in this condition, the wire with the Cu
17 matrix is in its most ductile state. The completed cable can then be leached
18 and Sn infiltrated.

19 The conductor of Example I contains within the niobium sheath 34.9%
20 copper by volume. High percentage of copper, i.e., greater spacing between
21 Nb filaments, would permit a more rapid rate of copper removal by chemical
22 etching but would also lower the current density of the conductor. To
23 maximize the current density, the etched conductor can be mechanically
24 compacted to increase the overall volume fraction of Nb before infiltration.

25 The infiltration step is performed in a continuous fashion similar to
26 that used for Sn dipped Nb tapes. The resident time in the Sn bath should be
27 as short as possible, only long enough to allow the wire to reach temperature
28 and to completely infiltrate and embed the filaments. This also avoids any
29 early brittle Nb₃Sn formation and the potential damage that can result from
30 further processing such as cabling, etc.

1 Approximately 2 wt% Nb is soluble in liquid Sn at 1000°C. Extended
2 time in liquid Sn baths at these temps can result in some Nb loss. Because of
3 this, the time for the infiltration should be very short. In addition, this can
4 largely be avoided by saturating the Sn prior to infiltration by addition of
5 pure Nb metal to the bath. This can be done for example by slowly running
6 ribbons or wires of pure Nb through the process first. At temperatures below
7 950°C, other non-superconducting compounds can form rapidly. For these
8 reasons the dipping temperatures should be at least 1000°C and above. It is
9 also important that the wire be cooled rapidly after infiltration to avoid the
10 formation of large grain size brittle intermetallic compounds of Cu and Sn.
11 Large copper additions to the Sn bath and its effects on Nb₃Sn layer growth
12 has been reported by J.S. Caslaw, Cryogenic, Feb. '71, pp. 51-59. The presence
13 of Cu "catalyze" the Nb₃Sn reaction and improves the surface of the Nb₃Sn.
14 Addition of up to 32%wt Cu resulted in substantial increase in Jc.

15 The Hc2 and Tc values of Nb₃Sn are influenced by the Nb alloy
16 composition. It is well known that selective additions of Ti and Ta can
17 increase these values. It's important to not only increase Hc2 and Tc but also
18 the Jc properties through proper flux pinning mechanisms. Smathers and
19 Swenaga's articles give detailed explanation of "Flux pinning" and the
20 methods currently employed. All of these methods can be applied in this
21 invention. Besides pure Nb, alloys of Nb-1%Zr, Nb-1.5%Ti, and Nb-7.5%Ta
22 can be used. The Ta and Ti can also be added to the Nb by means of a thin
23 surface layer of expanded Ta or Ti mesh. This would also help to reduce the
24 possibility of bridging between filaments. The Sn bath would include in
25 addition to Cu, smaller amounts of Mg and Ti.

26 The most important parameter determining the performance of Nb₃Sn
27 conductors is its current density. In the field of High Energy Physic,
28 accelerator magnets capable of operating in excess of 12 Tesla at 4.2°K are
29 needed. The dipole magnets for the Large Hardon Collider accelerator being
30 constructed at CERN can only operate at less than 10 Tesla at 1.9°K using

1 NbTi. For Nb₃Sn, the highest Jc values are currently being made by the 162
2 Internal Sn process and values as high as 2070 A/mm² at 12 Tesla and 4.2°K
3 have been reported. The bronze process appears to be limited to below 1,000
4 A/mm² and are thus not a factor. Values as high as 3,000 A/mm² are needed
5 for the next generation of accelerator magnets.

6 The area within the diffusion barrier contains only three components;
7 Nb, Cu and Sn. Increasing Jc can only be obtained by increase in the volume
8 fraction of Nb. This requires a proportional reduction in copper which
9 increase the Sn to Cu ratio. Copper simply acts as a carrier for the Sn; it does
10 not by itself participate directly toward increasing Jc. It does however
11 perform a vital function; that is to allow the successful co-processing of both
12 the bronze and Internal Sn Nb₃Sn conductors. Intensive efforts directed over
13 the past two decades toward optimizing the Nb:Cu:Sn ratios has all but
14 reached its limits due to the concomitant decrease in its fabricability as the Sn
15 fraction is increased. In the present invention, no such limitation exist. The
16 matrix alloy can be varied between pure Sn to pure Cu. Fabricability is not an
17 issue since the conductor is made initially with a pure copper matrix.

18 While the preferred method of application of the constraining sheath
19 has been described, it is recognized that alternatively, the sheath can be
20 separately applied to a finished copper niobium multi-filaments wire by
21 mechanical means. Several additional techniques may be employed as shown
22 in Figs. 5 through 9.

23 In Fig. 5, the constraining layer is spirally wrapped around the Cu-Nb
24 composite with adequate spacing between the spirals to allow access by the
25 leaching acid.

26 In Fig. 6, the constraining layer is woven in a braid around the Cu-Nb
27 composite with an open weave.

28 In Figs. 7 and 9, the Cu-Nb composites are carried in grooves of a
29 carrier element resistant to the leach, but sufficiently confining to constrain
30 the Cu free Nb filaments.

1 In Fig. 8, a Cu-Nb cable is twisted and flattened and then partially
2 surrounded by a constraining layer.

3 In all cases, the principal requirements of the constraining layer are to
4 allow for sufficient porosity for copper removal by acid, to be resistant to
5 nitric acid attack, to constrain and support the loose Nb filaments after Cu
6 removal and for subsequent infiltration with Sn. The constraining metal must
7 be one which will not react with Sn or, if Nb is used will be sufficiently thick
8 so that it will not be all converted to Nb₃Sn.

9 Transition metal carbides and nitrides such as NbN and NbC occur
10 with the B1 (NaCl) crystal structure. Niobium nitride has been shown to
11 have a transition temperature approaching 19°K. These important
12 compounds are described in "Treatise on Material Science and Technology",
13 Vol. 14, Metallurgy of Superconducting Materials, 1979 edited by Thomas
14 Luhman and David Dew-Hughes, pages 429-432.

15 The present invention can be employed for forming NbN. Exactly the
16 same steps
17 are utilized, that of porous outer sheath surrounding a copper matrix with Nb
18 filaments from which the copper matrix is removed. Instead of the Sn
19 infiltration step, a nitrogen containing atmosphere is introduced in which the
20 niobium filaments are converted into niobium nitride (NbN) at elevated
21 temperatures.

22 From a practical point of view, the gaseous phase reaction is a simpler
23 and cleaner process than the handling of liquid Sn in the temperature range of
24 1000°C. The NbN filaments can be used as reacted or may require a metal
25 infiltration for improved stability reasons as described by L.T. Summers, J.R.
26 Miller, "The Influence of Liquid Metal Infiltration on Superconducting
27 Characteristics of Niobium Nitride," Advanced in Cryogenic Eng., Vol. 34,
28 pp. 835-842, 1987.

29 EXAMPLE I

1 19 holes 2 are drilled into a 15.3 cm diameter bar 1 of copper 63.5 cm
2 long 1 as shown in Fig. 1a. The holes are 2.57 cm in diameter and run the
3 length of the bar in parallel fashion. The pattern of holes is as shown in Fig.
4 1a. The shortest distance between any two holes is 5.08 mm. A 1.27 cm insert
5 is machined into each end of the copper bar. The insets are necessary in order
6 that a copper nose and tail may be attached later. The copper bar containing
7 the holes, a copper nose, and a copper tail are etched clean in a nitric acid
8 solution, they are rinsed in water, rinsed a second time in methanol, and are
9 then dried. 19 niobium bars, 2.54 cm in diameter and 61 cm long 2 are wiped
10 clean with acetone and are inserted into the holes in the copper bar 3. The
11 nose and tail are tungsten inert gas (TIG) welded into place, and the billet is
12 evacuated at a temperature of 427°C to a pressure of 10^{-6} torr. The billet is
13 then sealed as shown in Fig. 1b.

14 In preparation for extrusion, the billet is heated at a temperature of
15 816°C for a period of three hours. The billet is then extruded to a diameter of
16 2.54 cm. The extruded rod is cropped to ensure uniformity, and the cropped
17 rod is cold drawn at an areal reduction rate of 20% per die pass to a final
18 hexagonal diameter of 3.48 mm. That is, the final wire shape is hexagonal and
19 the distance from flat to flat across the hexagon is 3.48 mm. At this size, the
20 niobium filament diameter is 0.61 mm.

21 The wire is straightened and cut to 61 cm lengths. Pure copper rod is
22 drawn to 3.48 mm diameter hexagonal wire and is straightened and cut to 61
23 cm lengths in the same manner as the wire containing the Nb filaments. Both
24 types of filaments are cleaned in nitric acid in the same manner as was the
25 primary billet. 1045 of the Nb-containing filaments 4 are stacked in
26 symmetrical fashion.

27 A section of 0.64 mm thick Nb sheet 7, 45.7 cm wide and 610 cm long,
28 is wiped clean with acetone and is inserted circumferentially into a clean
29 copper can 8 having an internal diameter 14.5 cm, an external diameter 16.5
30 cm, and a length of 63.5 cm 7. The sheet 7 overlays by 0.3 cm so as to ensure a

1 continuous layer. The long dimension of the sheet runs along the can length.
2 The stack of filaments is inserted into the niobium-lined can (see Fig. 2) and
3 the copper nose and tail are electron beam welded into place under a vacuum
4 of 10^{-4} torr. The billet is then hot isostatically pressed at a pressure of 104 MPa
5 and temperature of 650°C for four hours. The isostatically pressed billet is
6 machined to a diameter of 15.3 cm, and the billet is prepared for extrusion by
7 heating for three hours at 816°C. The billet is then extruded to a diameter of
8 2.54 cm.

9 The extruded rod is cropped to ensure uniformity. It is then drawn at
10 an areal reduction rate of 20% per die pass to a diameter of 1.02 mm and
11 twisted. At this wire diameter, the diameter of the Nb filaments is 4.06
12 microns, and the thickness of the niobium sheath is 42.6 microns. The total
13 volume fraction of Nb filaments within the Nb sheath is 34.9%.

14 Thereafter, the Nb outer sheath 7 is perforated by means such as
15 slotted rolls as mentioned previously and the product is leached in
16 $\text{HNO}_3/\text{H}_2\text{O}$ at 100°C for 60 min. to remove the copper separating the Nb
17 filaments. The copper-free mass of Nb filaments is then preferably immersed
18 in a tin bath at 1000°C to allow for maximum fluidity and surface tension of
19 the Sn bath. An inert atmosphere of Argon is used to avoid oxidation.
20 Dipping resident time in the Sn bath should be as short as possible (less than
21 10 sec) to minimize Nb_3Sn formation at this stage and maximize the ductility
22 for further processing; i.e. cabling.

23 EXAMPLE II

24 In Example I, a continuous sheath, as shown in Fig. 2, was employed
25 and at the final size the conductor was mechanically perforated as shown in
26 Figs. 3a and 3b to allow for the removal of the copper matrix by acid leaching
27 followed by liquid tin infiltration at high temperatures. It was also shown
28 that the sheath can be applied separately after the conductor has been
29 fabricated by means of taping Fig. 5, Braiding Fig. 6, or by mechanically
30 confining the conductor into a support structure as shown in Figs. 7, 8 and 9.

1 A simpler and considerably less expensive method has been found
 2 which accomplishes the same objective. The sheath is constructed exactly as
 3 in Example I except now a narrow opening is left which is parallel to and runs
 4 the length of the filaments shown in Fig. 10.

5 The size of the opening can be adjusted to permit rapid copper removal
 6 of the matrix by acid leaching and still retain the sheath's ability to constrain
 7 and support the filaments. Following the final reduction, twisting and copper
 8 removal, a product which is an exact duplicate of the taping example of Fig. 5
 9 is remarkably produced. Several variations are possible in the sheath design.
 10 For example, more than one opening can be used.

11 The twisting action causes the outer filaments to stretch more than the
 12 inner strands and when the copper matrix is removed, the outer filaments are
 13 under tension and act to compress and constrain the inner bundle of
 14 filaments. It has been observed that untwisted or lightly twisted, the outer
 15 filaments will tend to exfoliate at the sheath opening.

16 This conductor was leached in a $\text{HNO}_3/\text{H}_2\text{O}$ 50/50 acid solution at
 17 100°C to completely remove the copper matrix. The following Cu-Sn alloys
 18 were then used for infiltration experiments:

Cu wt%	Sn wt%
87	13
67	33
50	50
25	75
20	80
10	90
0	100

19 Successful infiltration at 1000°C was obtained for all alloys with the
 20 exception of the 13% Sn alloy. This alloy has a liquidus temperature of 1000°C

1 and would have required a temperature of at least 1200°C which was beyond
2 the temperature capability of our small laboratory furnace.

3 The 33% Sn alloy sample was subsequently heat treated at 675°C for 24
4 and 48 hours. Metallographic examination of the cross section for the 48 hour
5 sample reveals a substantial Nb₃Sn reacted layer, averaging 4-6 micron in
6 thickness both in the filaments and in the surrounding sheath.

7 As shown in Fig. 4, a central copper core can be used. As a typical
8 requirement, up to 40% copper is needed to insure stable conductor
9 performance. To prevent Sn contamination of the copper core, a Ta protective
10 barrier is employed in Fig. 4. It should be recognized that this structure by
11 itself contributes a significant amount of support and that together with the
12 external sheath of this invention would combine to protect the fragile Nb₃Sn
13 filaments inside. It has been shown that a high strength copper containing Nb
14 composite has been successfully used in conjunction with Nb₃Sn conductors
15 and can be used in place of pure copper. (See advances in Cryogenic Eng.,
16 Vol. 42, Plenum Press, NY 1996, pages 1423-1432).

17

1 1. A process for manufacturing a Nb₃Sn superconductor comprising
2 the steps of establishing multiple niobium components in a billet of a ductile
3 metal, working the composite billet through a series of reduction steps to
4 form said niobium components into elongated elements, each said element
5 having a thickness on the order of 1 to 25 microns, surrounding said billet
6 with a porous confining layer of an acid resistant metal, immersing said
7 confined billet in an acid to remove said ductile metal from between the
8 niobium elements while the niobium elements remain confined by said
9 porous layer, immersing the confined mass of niobium elements in a liquid
10 metal containing tin to coat said niobium elements with said liquid metal and
11 subsequently reacting said tin with the Nb filaments to form Nb₃Sn.

12 2. The process of claim 1 wherein said reaction is accomplished after
13 said filaments are formed into a magnetic coil.

14 3. The process of claim 1 wherein the liquid metal bath is pure tin.

15 4. The process of claim 1 wherein the liquid metal bath is a copper
16 alloy containing up to 95 wt% Sn.

17 5. The process of claim 1 wherein the liquid metal bath is a copper
18 alloy containing up to 95 wt% Sn and at least 13 wt% Sn.

19 6. A process for manufacturing a niobium-based superconductor
20 selected from the group consisting of Nb₃Sn, Nb₃Al, NbN, and NbC
21 comprising the steps of establishing multiple niobium components in a billet
22 of a ductile metal, working the composite billet through a series of reduction
23 steps to form said niobium components into elongated elements, each said
24 element having a thickness on the order of 1 to 25 microns, surrounding said
25 billet with a porous confining layer of an acid resistant metal, immersing said
26 confined billet in an acid to remove said ductile metal from between the
27 niobium elements while the niobium elements remain confined by said
28 porous layer, exposing the confined mass of niobium elements to a material
29 capable of reacting with Nb to form a superconductor.

30 7. The process of claim 6 wherein said material is nitrogen.

1 8. A process for manufacturing a A-15 or B1 type compound
2 superconductor comprising the steps of establishing multiple primary metal
3 component in a billet of a ductile metal, working the composite billet through
4 a series of reduction steps to form said primary metal components into
5 elongated elements, each said element having a thickness in the order of 1 to
6 25 microns, surrounding said elements with a porous confining layer of an
7 acid resistant metal, immersing said confined elements in an acid to remove
8 said ductile metal from between the primary metal elements while the
9 primary elements remain confined by said porous layer, contacting the
10 confined mass of primary metal elements with a reactant and reacting the
11 primary metal elements with the reactant to form the A-15 or B1
12 superconducting compound.

13 9. The process of claim 1 wherein said billet is surrounded by said
14 porous layer prior to the last reduction step.

15 10. The process of claim 1 wherein said porous layer is created by
16 twisting the reduced billet so that outer elements in the billet serve to confine
17 inner elements in the billet when the ductile metal is removed from the billet.

18 11. The process of claim 1 wherein said porous layer is created by
19 running at least one outer element along the outer surface of the reduced
20 billet and twisting the reduced billet so that outer elements in the billet serve
21 to confine inner elements in the billet when the ductile metal is removed from
22 the billet.

23

1 / 5

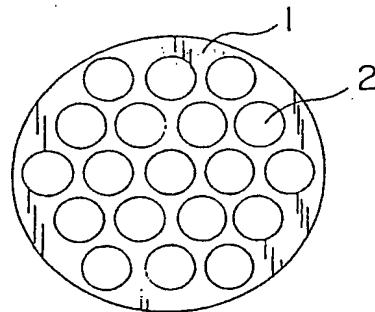


FIG. 1A

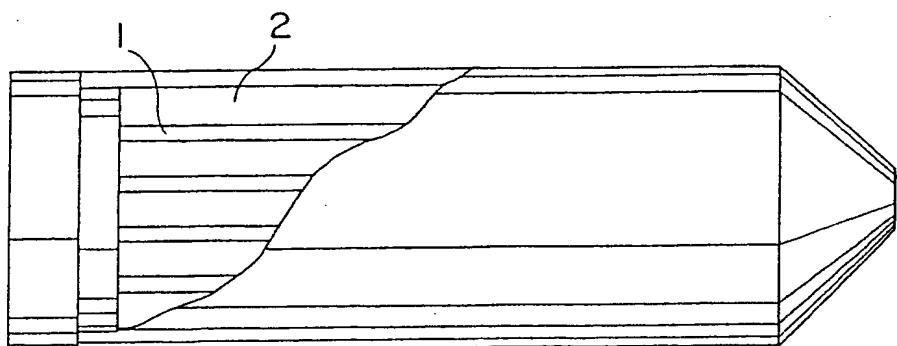


FIG. 1B

2 / 5

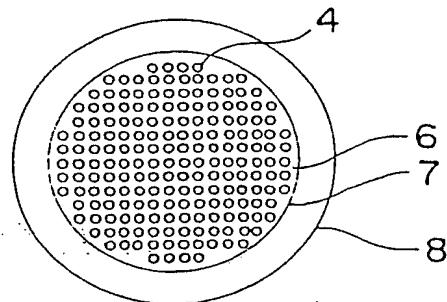


FIG. 2

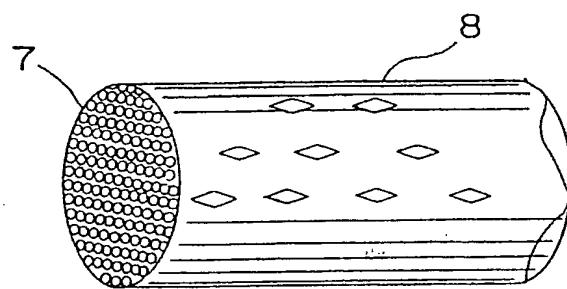


FIG. 3A

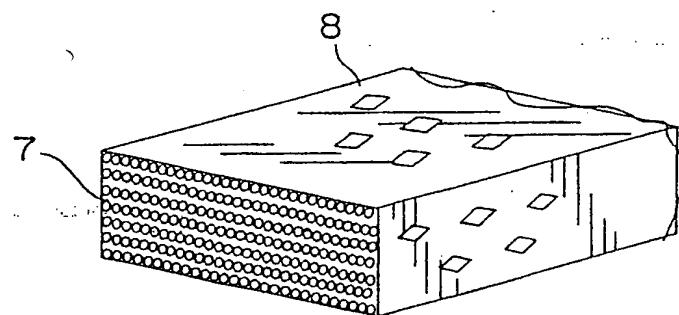
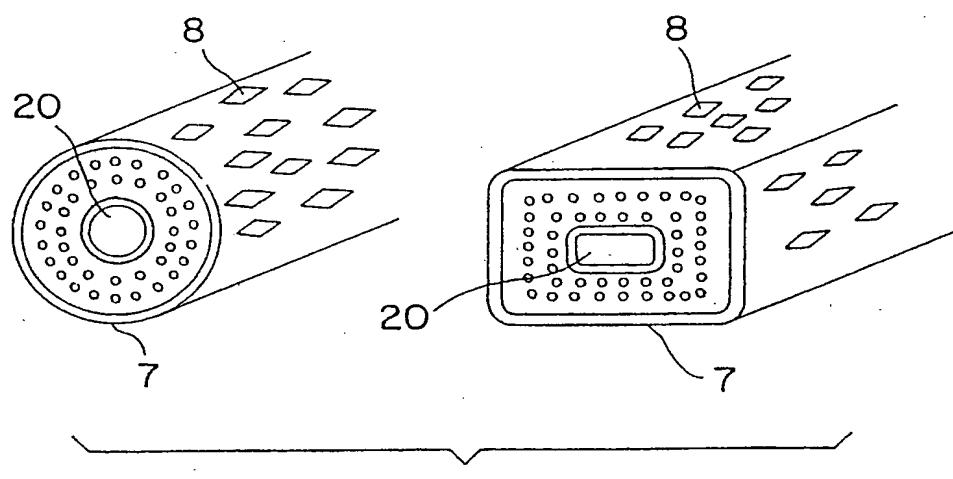


FIG. 3B



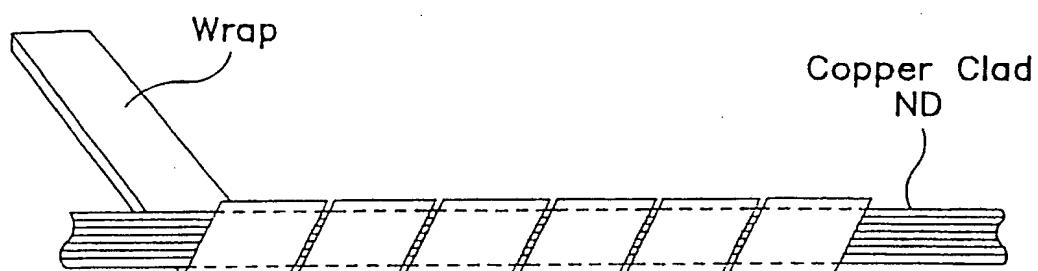


FIG. 5

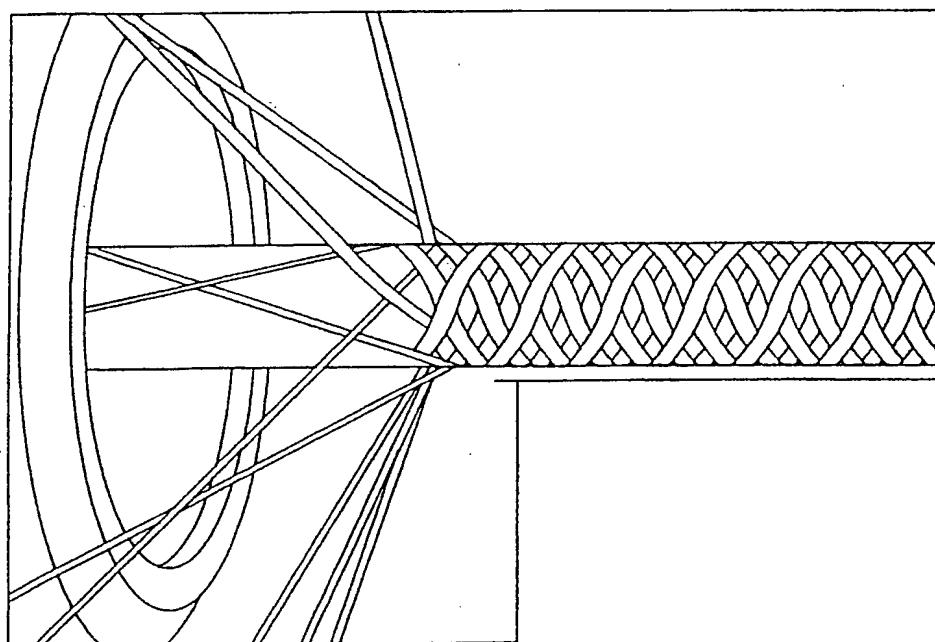


FIG. 6

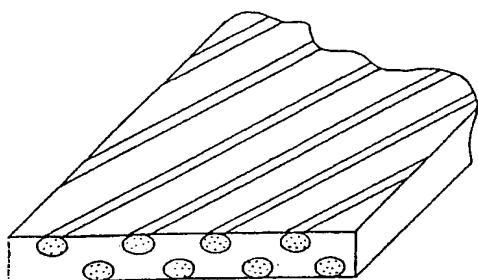


FIG. 7

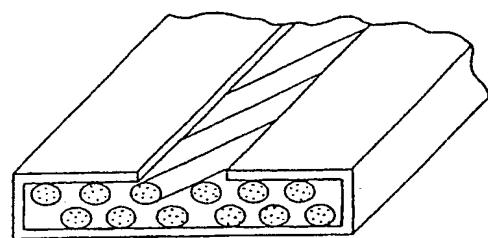


FIG. 8

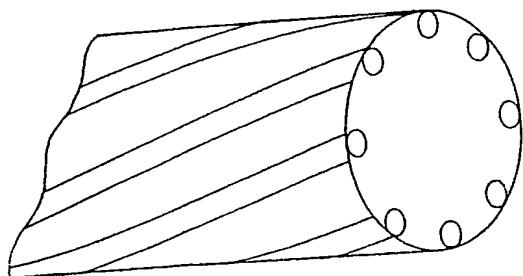


FIG. 9

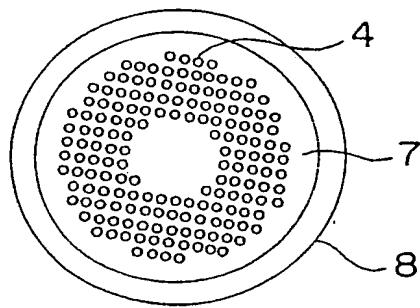


FIG. 10

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 00/10464

A. CLASSIFICATION OF SUBJECT MATTER
 IPC 7 C23C2/00 H01L39/00 H01B12/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 IPC 7 C23C B32B H01L H01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 534 219 A (MARANCIK WILLIAM G ET AL) 9 July 1996 (1996-07-09) the whole document ---	1-11
A	US 5 174 831 A (RUDZIAK MARK K ET AL) 29 December 1992 (1992-12-29) the whole document ---	1-11
A	US 5 869 196 A (RUDZIAK MARK K ET AL) 9 February 1999 (1999-02-09) cited in the application the whole document -----	1-11

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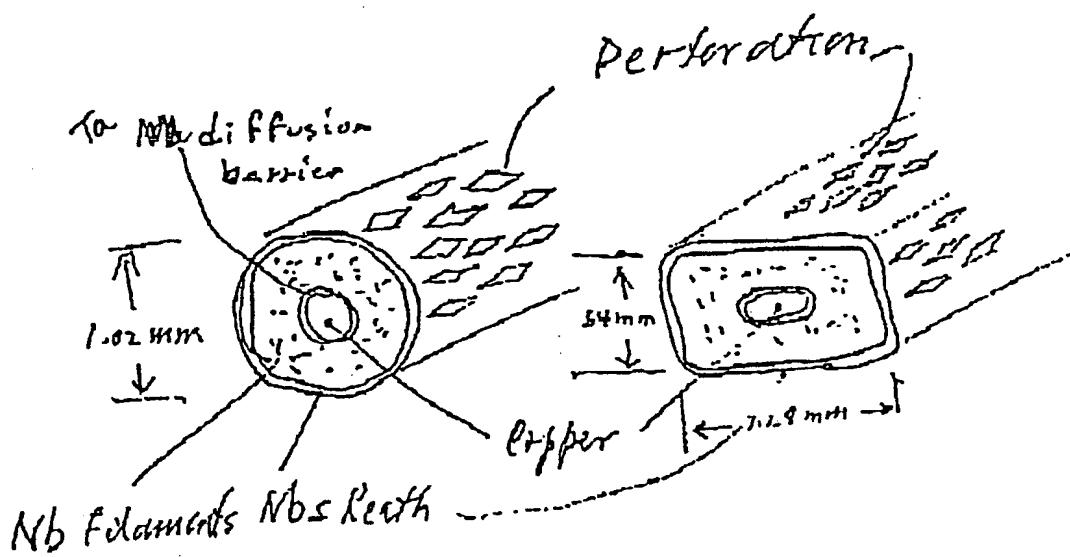
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US 5534219	A	09-07-1996		JP 10512923 T WO 9532828 A		08-12-1998 07-12-1995
US 5174831	A	29-12-1992		US 4925741 A US 5158620 A US 5160794 A US 5160550 A US 5174830 A US 5230748 A US 5445681 A		15-05-1990 27-10-1992 03-11-1992 03-11-1992 29-12-1992 27-07-1993 29-08-1995
US 5869196	A	09-02-1999		EP 0968083 A WO 9828129 A		05-01-2000 02-07-1998

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(21) International Application Number: PCT/US00/10464		(81) Designated States: CN, JP, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).	
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(30) Priority Data:		Published	
60/130,079 60/144,430 60/165,099 09/532,362	20 April 1999 (20.04.99) 16 July 1999 (16.07.99) 12 November 1999 (12.11.99) 21 March 2000 (21.03.00)	US US US US	Without international search report and to be republished upon receipt of that report.
(71) Applicant: COMPOSITE MATERIALS TECHNOLOGY, INC. [US/US]; 830 Boston Turnpike Road, Shrewsbury, MA 01545 (US).			
(72) Inventor: WONG, James; 25 Cameron Road, Wayland, MA 01778 (US).			
(74) Agents: SOLOWAY, Norman, P. et al.; Hayes, Soloway, Hennessey, Grossman & Hage, PC, 175 Canal Street, Manchester, NH 03101 (US).			

(54) Title: CONSTRAINED FILAMENT NIOBium-BASED SUPERCONDUCTOR COMPOSITE AND PROCESS OF FABRICATION



(57) Abstract

A niobium-based superconductor is manufactured by establishing multiple niobium components in a billet of a ductile metal, working the composite billet through a series of reduction steps to form the niobium components into elongated elements, each niobium element having a thickness on the order of 1 to 25 microns, surrounding the billet prior to the last reduction step with a porous confining layer of an acid resistant metal, immersing the confined billet in an acid to remove the ductile metal from between the niobium elements while the niobium elements remain confined by said porous layer, exposing the confined mass of niobium elements to a material capable of reacting with Nb to form a superconductor.

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1 CONSTRAINED FILAMENT NIOBIUM-BASED SUPERCONDUCTOR COMPOSITE
2 AND PROCESS OF FABRICATION
3

4 The present invention pertains to the fabrication of A-15 type
5 multifilament composite superconductors (By "A-15" is meant the inter
6 metallic compounds having β W structure). These include Nb_3Sn , and Nb_3Al
7 and are important because of their superior high field properties.
8 Unfortunately, they are brittle compounds, difficult to make as fine filaments
9 and as a result are very expensive. For these reasons, the ductile NbTi
10 superconductors has dominated the commercial market even though its
11 maximum magnetic field are limited to less than 8 Tesla. Significant
12 improvements are needed in order to commercialize the A-15 conductors and
13 to extend the useful magnetic fields to the 12 Tesla range on a cost effective
14 basis. The present invention is also applicable to the production of the "B1"
15 superconductors NbN and NbC.

16 A detailed description of present day methods currently being used in
17 the industry is described in an article entitled "A-15 Superconductors" in the
18 Metals Handbook, Tenth Edition, Volume 2 on pages 1060-1077, authored by
19 David B. Smathers. Two processes are currently being used. One employs a
20 bronze alloy as the matrix, the other a combination of pure copper and a pure
21 Sn core. The first is known as the "Bronze Process" and the latter the
22 "Internal Tin Process". The bronze matrix contains up to 13% Sn work
23 hardens rapidly and requires frequent annealing steps. These anneals are
24 avoided with the internal tin process. However, the cold drawing in the
25 Internal Tin process can result in poor bonding, degraded filament quality
26 and poor yields. After final drawing and twisting, both types of conductors
27 are heated to approximately 700°C for 200 hours or more to form Nb_3Sn .
28 Magnets are made exclusively by the Wind and React method.

29 The current densities that are obtained are substantially below what is
30 theoretically possible based on experimental short sample data. Contributing

1 to this problem is the low reaction temp of up to 700°C, requiring hundreds of
2 hours of reaction heat treatment. As the Sn is depleted, the Sn gradient is
3 reduced which further limits the reaction. Unreacted Nb in the Nb filament
4 can be left and Kirkendall type voids are formed in the residual matrix
5 resulting in a lowering of the current density and mechanical properties of the
6 conductor.

7 Significant improvements are needed to improve the high field
8 performance and to reduce the cost of these important A-15 conductors.

9 In the fabrication of Nb₃Sn superconducting wire, a barrier, usually
10 tantalum or a tantalum alloy is employed to prevent tin contamination of the
11 stabilizing copper on the exterior of the wire during heat treatment. The
12 process is described in the article by David B. Smathers. While the porous
13 metal sheath described in the present invention is similar to the barrier used
14 in Nb₃Sn conductor fabrication, application of the technology in this invention
15 is entirely unique.

16 US Patent Nos. 5,034,857 and 5,869,196 by Wong, discloses a novel
17 approach to the production of very fine valve metal filaments, preferable
18 tantalum, for capacitor use. The benefits of fine filaments relative to fine
19 powders are higher purity, lower cost, uniformity of cross section, and ease of
20 dielectric infiltration, while still maintaining high surface area for
21 anodization. The uniformity of cross section results in capacitors with high
22 specific capacitance, lower ESR and ESL, and less sensitivity to forming
23 voltage and sintering temperature as compared to fine powder compacts.
24 Other patents involving valve metal filaments and fibers, their fabrication, or
25 articles made therefrom include US Patent Nos. 3,277,564 (Webber), 3,379,000
26 (Webber), 3,394,213 (Roberts), 3,567,407 (Yoblin), 3,698,863 (Roberts) 3,742,369
27 (Douglass), 4,502,884 (Fife), 5,306,462 (Fife) and 5,245,514 (Fife).

28 The prior art relating to the fabrication of A-15 conductors can be
29 obtained by reading both Smather's article and "Filamentary A-15
30 Superconductors" by Masaki Suenaga and Alan F. Clark, Plenum Press, N.Y.

1 Cryogenic Material Series (published 1980). In this book, the article by C.H.
2 Rosner, B.A. Zeitlin, R.CX. Schwall, M.S. Walker and G.M. Ozeryansky
3 entitled "Review of Superconducting Activities at IGC on A-15 Conductors"
4 pages 67-79, specifically summarizes the earlier developments. Initially,
5 powder metallurgy methods were employed followed soon by surface
6 diffusion of liquid Sn of both Nb tapes and wires. Allen 3,218,693 patented a
7 method where Sn coated Nb ribbons and wire were reacted to form Nb₃Sn at
8 temperatures between 800°C to 1000°C. Similar products were also made by
9 General Electric and later by IGC. The Nb wires in cable form, were Sn
10 dipped, wound into a magnet and reacted; D.F. Martin et al Patent No.
11 3,429,032. A subsequent article, by Scanlan and Fietz, "MultiFilamentary
12 Nb₃Sn for Superconducting Generator application", IEEE Trans. MAG-11
13 page 287, March '75, describes fabrication of a Nb₃Sn cable employing
14 electroplated Sn as the Sn source.

15 A new approach is necessary to improve the processing of Nb₃Sn
16 conductors. In the early 1960's, pure Nb tapes, wires and cable were dipped
17 in molten Sn baths which was then reacted at high temperatures to form
18 Nb₃Sn. Because Nb₃Sn is brittle, a ductile substrate of unreacted Nb was left
19 to permit handling and subsequent winding into magnets. However, the
20 need for stable, fine filaments and twisted conductors soon made this method
21 obsolete.

22 Wong's patent '196 describes a process used to manufacture Ta
23 capacitors where Ta multifilaments are made in a constraining sheath. This
24 process describes the removal of the copper matrix after the final forming
25 operation. The advantages of the external sheath is that final packaging of the
26 filaments are unnecessary since the filaments are now constrained and
27 supported by the outer sheath. Furthermore, the area inside the sheath is
28 exactly determined as is the volume fraction of Ta.

29 A precursor wire, containing fine Nb filaments enclosed in a
30 constraining sheath which can act as a supporting structure is produced.

1 Upon the removal of the copper matrix, and employing a liquid Sn dipping
2 process, Sn or a CuSn alloy is used to infiltrate and surround the Nb
3 filaments. The significant advantage here is that the need for subsequent wire
4 drawing is completely eliminated as is the co-processing and low yield
5 difficulties of present day Nb₃Sn conductors. The ability to easily increase the
6 Sn concentration can result in substantial improvement in current density
7 over present day conductors. The sheath, in the preferred embodiments, is
8 made of Nb although Ta and stainless steel could also be used. The sheath is
9 fabricated by methods as described in US Patent No. 5,869,196 by Wong. The
10 billet is processed in the normal manner by extrusion and wire drawing to the
11 final size. The copper matrix is then removed from this precursor wire and
12 replaced with a Sn or CuSn alloy matrix. Final reaction heat treatments are
13 then used to convert the Nb to Nb₃Sn.

14 Fig. 1 is a schematic depiction of the primary billet used in the present
15 invention, Fig. 1a showing a transverse cross section, and Fig. 1b showing a
16 cutaway view revealing the longitudinal disposition of the billet components.

17 Fig. 2 is a schematic depiction of the transverse cross section of the
18 secondary billet used in the process of the present invention.

19 Fig. 3 is a schematic depiction of the product of the preferred
20 embodiment of the present invention, Fig. 3a showing the product as a
21 cylindrical body, and Fig. 3b showing the product after shaping into a
22 rectangular body.

23 Fig. 4 is similar to Fig. 3 but shows the internal copper core to achieve
24 stabilization.

25 Figs. 5-9 show additional systems for constraining the niobium
26 filaments during and after the step of acid leaching of the copper.

27 Fig. 10 is a schematic depiction of the primary billet used in the
28 preferred embodiment of the present invention.

29 This invention is directed to the fabrication of the fine metal filaments
30 for use as the base for reaction with tin (for example) to produce A-15

1 superconductors in situ. A very small body of constrained filaments and a
2 method for manufacture are disclosed. The invention will be of greatest value
3 in the superconductor industry, which seeks to develop increasingly high
4 magnetic field A-15 superconductors. The metal is selected from among the
5 metallic elements, niobium and in particular, the A-15 compounds of Nb. In a
6 preferred form, the product of the present invention, the metal filaments are
7 of a diameter less than 50 microns. They are constrained within a cylindrical
8 sheath, also made of metal, which has a wall thickness of 100 microns or less.
9 The metal that forms the sheath is preferably the same as that of the filaments,
10 but it is not necessarily so; tantalum can be used as well as stainless steel.
11 Multifilament conductors suitable for use as superconductors are formed
12 through the reduction of a metal billet consisting of multiple filaments of an
13 appropriate refractory metal, preferably niobium, contained within, and
14 spaced apart by, a ductile metal, preferably copper. The Nb filaments are
15 elongated and substantially parallel within the billet as shown in Fig. 2. The
16 array of Nb filaments 4 within the billet is surrounded by a confining layer of
17 metal 7. This metal 7 is preferably, but not necessarily, the same as that which
18 forms the filaments. The metal layer 7 preferably completely surrounds the
19 Nb filament array 4 circumferentially and runs the full length of the filaments.
20 The layer is separated from the filament array 4 by the same ductile metal 6
21 (e.g. Cu) that serves to separate the filaments 4 from each other. This same
22 ductile metal 6 can also form the surface of the billet, preventing exposure of
23 the confining metal layer during heating etc. The billet is reduced by
24 conventional means, such as extrusion and wire drawing. The confining
25 metal sheath 7 is then perforated (as shown in Figs. 3a and 3b at 8) such that
26 the mineral acid can readily diffuse through the porous layer and remove the
27 ductile copper separating the Nb filaments. It is important that these
28 perforations 8 should be designed such that the sheath retains its ability to
29 restrain and support the loose Nb filaments 4. More importantly, they should
30 not substantially weaken the strength or ductility of the entire composite.

1 Preferably, the perforation 8 can be accomplished by mechanically rolling the
2 wire in a rolling mill with the desired perforation pattern in a continuous
3 matter. Other means can be also employed, such as selective chemical
4 etching, laser drilling, etc. as would be apparent to one skilled in the art. The
5 constraining metal must be one that is inert to the acid used to dissolve the
6 copper.

7 Typical shapes would be a circular Fig. 3a or rectangular cross section
8 Fig. 3b. An advantage for the rectangular shape is that the distance for the
9 acid to penetrate for complete copper removal is reduced. Internal copper
10 stabilization can be introduced as shown in Fig. 4. The Ta clad copper
11 appears as a central core with a Ta diffusion barrier layer and it also reduces
12 the leaching time. Thereafter, the copper-free confined bundle of Nb
13 filaments is infiltrated with liquid Sn or CuSn alloy to thoroughly coat and
14 embed each Nb filament in a solid Sn or CuSn alloy matrix. The Sn is then
15 reacted with Nb to form Nb₃Sn in a separate step. Temperatures between
16 700°C to 1100°C are used, both performed in an inert atmosphere or vacuum
17 chamber. The Nb-filaments may be reacted partially, completely or it can be
18 completed at a later stage in the manufacture, e.g. after cabling or winding in
19 a magnet.

20 In one preferred form of the invention, the Nb filaments, at the
21 completion of the mechanical reduction step, will have a diameter on the
22 order of one to twenty-five microns. In this preferred final form of the
23 composite, the Nb filaments are separated by the Cu matrix and the Nb-Cu
24 structure is surrounded by a 50 micron or less thick layer of Nb having an
25 effective porosity of 50% or less. When this composite is immersed in an acid
26 leaching bath of HNO₃ and H₂O at 100°C, the copper is removed in about 60
27 min, leaving a bundle of micron size Nb filaments confined by a porous Nb
28 sheath. When this copper-free mass of Nb filaments is immersed in a Sn alloy
29 bath between 700°C to 1100°C the surface tension of the molten Sn bath and
30 the capillarity of the bundle of Nb filaments enclosed within the sheath draws

1 the tin into the bundle where it completely surrounds each Nb filament. The
2 Sn is then reacted with the Nb to form the Nb₃Sn compound at a later stage of
3 manufacturing.

4 As will be apparent to one skilled in the field of metallurgy, this
5 porosity can be achieved, for example, by mechanically perforating the
6 confining layer wherein the perforations 8 are uniformly spaced about 0.25
7 mm apart with a diamond shape size of 0.13 mm x 0.25 mm, as shown in Figs.
8 3a and 3b.

9 When the acid leaching of the copper from the Nb-Cu matrix results in
10 unacceptably high amounts of surface contamination on the Nb filaments,
11 these contaminates can be removed by the techniques described on page 9,
12 lines 38-55, in my earlier patent 5,869,169. Such deoxidation treatments may
13 improve the wetting of the Nb filaments by the liquid Sn alloy as well.

14 Prior to copper removal, multiple strands of wire can be cabled
15 together and compacted if required. This would avoid any mechanical
16 damage to the Nb filaments because, in this condition, the wire with the Cu
17 matrix is in its most ductile state. The completed cable can then be leached
18 and Sn infiltrated.

19 The conductor of Example I contains within the niobium sheath 34.9%
20 copper by volume. High percentage of copper, i.e., greater spacing between
21 Nb filaments, would permit a more rapid rate of copper removal by chemical
22 etching but would also lower the current density of the conductor. To
23 maximize the current density, the etched conductor can be mechanically
24 compacted to increase the overall volume fraction of Nb before infiltration.

25 The infiltration step is performed in a continuous fashion similar to
26 that used for Sn dipped Nb tapes. The resident time in the Sn bath should be
27 as short as possible, only long enough to allow the wire to reach temperature
28 and to completely infiltrate and embed the filaments. This also avoids any
29 early brittle Nb₃Sn formation and the potential damage that can result from
30 further processing such as cabling, etc.

1 Approximately 2 wt% Nb is soluble in liquid Sn at 1000°C. Extended
2 time in liquid Sn baths at these temps can result in some Nb loss. Because of
3 this, the time for the infiltration should be very short. In addition, this can
4 largely be avoided by saturating the Sn prior to infiltration by addition of
5 pure Nb metal to the bath. This can be done for example by slowly running
6 ribbons or wires of pure Nb through the process first. At temperatures below
7 950°C, other non-superconducting compounds can form rapidly. For these
8 reasons the dipping temperatures should be at least 1000°C and above. It is
9 also important that the wire be cooled rapidly after infiltration to avoid the
10 formation of large grain size brittle intermetallic compounds of Cu and Sn.
11 Large copper additions to the Sn bath and its effects on Nb₃Sn layer growth
12 has been reported by J.S. Caslaw, Cryogenic, Feb. '71, pp. 51-59. The presence
13 of Cu "catalyze" the Nb₃Sn reaction and improves the surface of the Nb₃Sn.
14 Addition of up to 32%wt Cu resulted in substantial increase in Jc.

15 The Hc2 and Tc values of Nb₃Sn are influenced by the Nb alloy
16 composition. It is well known that selective additions of Ti and Ta can
17 increase these values. It's important to not only increase Hc2 and Tc but also
18 the Jc properties through proper flux pinning mechanisms. Smathers and
19 Swenaga's articles give detailed explanation of "Flux pinning" and the
20 methods currently employed. All of these methods can be applied in this
21 invention. Besides pure Nb, alloys of Nb-1%Zr, Nb-1.5%Ti, and Nb-7.5%Ta
22 can be used. The Ta and Ti can also be added to the Nb by means of a thin
23 surface layer of expanded Ta or Ti mesh. This would also help to reduce the
24 possibility of bridging between filaments. The Sn bath would include in
25 addition to Cu, smaller amounts of Mg and Ti.

26 The most important parameter determining the performance of Nb₃Sn
27 conductors is its current density. In the field of High Energy Physic,
28 accelerator magnets capable of operating in excess of 12 Tesla at 4.2°K are
29 needed. The dipole magnets for the Large Hardon Collider accelerator being
30 constructed at CERN can only operate at less than 10 Tesla at 1.9°K using

1 NbTi. For Nb₃Sn, the highest J_c values are currently being made by the
2 Internal Sn process and values as high as 2070 A/mm² at 12 Tesla and 4.2°K
3 have been reported. The bronze process appears to be limited to below 1,000
4 A/mm² and are thus not a factor. Values as high as 3,000 A/mm² are needed
5 for the next generation of accelerator magnets.

6 The area within the diffusion barrier contains only three components;
7 Nb, Cu and Sn. Increasing J_c can only be obtained by increase in the volume
8 fraction of Nb. This requires a proportional reduction in copper which
9 increase the Sn to Cu ratio. Copper simply acts as a carrier for the Sn; it does
10 not by itself participate directly toward increasing J_c. It does however
11 perform a vital function; that is to allow the successful co-processing of both
12 the bronze and Internal Sn Nb₃Sn conductors. Intensive efforts directed over
13 the past two decades toward optimizing the Nb:Cu:Sn ratios has all but
14 reached its limits due to the concomitant decrease in its fabricability as the Sn
15 fraction is increased. In the present invention, no such limitation exist. The
16 matrix alloy can be varied between pure Sn to pure Cu. Fabricability is not an
17 issue since the conductor is made initially with a pure copper matrix.

18 While the preferred method of application of the constraining sheath
19 has been described, it is recognized that alternatively, the sheath can be
20 separately applied to a finished copper niobium multi-filaments wire by
21 mechanical means. Several additional techniques may be employed as shown
22 in Figs. 5 through 9.

23 In Fig. 5, the constraining layer is spirally wrapped around the Cu-Nb
24 composite with adequate spacing between the spirals to allow access by the
25 leaching acid.

26 In Fig. 6, the constraining layer is woven in a braid around the Cu-Nb
27 composite with an open weave.

28 In Figs. 7 and 9, the Cu-Nb composites are carried in grooves of a
29 carrier element resistant to the leach, but sufficiently confining to constrain
30 the Cu free Nb filaments.

1 In Fig. 8, a Cu-Nb cable is twisted and flattened and then partially
2 surrounded by a constraining layer.

3 In all cases, the principal requirements of the constraining layer are to
4 allow for sufficient porosity for copper removal by acid, to be resistant to
5 nitric acid attack, to constrain and support the loose Nb filaments after Cu
6 removal and for subsequent infiltration with Sn. The constraining metal must
7 be one which will not react with Sn or, if Nb is used will be sufficiently thick
8 so that it will not be all converted to Nb₃Sn.

9 Transition metal carbides and nitrides such as NbN and NbC occur
10 with the B1 (NACL) crystal structure. Niobium nitride has been shown to
11 have a transition temperature approaching 19°K. These important
12 compounds are described in "Treatise on Material Science and Technology",
13 Vol. 14, Metallurgy of Superconducting Materials, 1979 edited by Thomas
14 Luhman and David Dew-Hughes, pages 429-432.

15 The present invention can be employed for forming NbN. Exactly the
16 same steps
17 are utilized, that of porous outer sheath surrounding a copper matrix with Nb
18 filaments from which the copper matrix is removed. Instead of the Sn
19 infiltration step, a nitrogen containing atmosphere is introduced in which the
20 niobium filaments are converted into niobium nitride (NbN) at elevated
21 temperatures.

22 From a practical point of view, the gaseous phase reaction is a simpler
23 and cleaner process than the handling of liquid Sn in the temperature range of
24 1000°C. The NbN filaments can be used as reacted or may require a metal
25 infiltration for improved stability reasons as described by L.T. Summers, J.R.
26 Miller, "The Influence of Liquid Metal Infiltration on Superconducting
27 Characteristics of Niobium Nitride," Advanced in Cyrogenic Eng., Vol. 34,
28 pp. 835-842, 1987.

29 EXAMPLE I

1 19 holes 2 are drilled into a 15.3 cm diameter bar 1 of copper 63.5 cm
2 long 1 as shown in Fig. 1a. The holes are 2.57 cm in diameter and run the
3 length of the bar in parallel fashion. The pattern of holes is as shown in Fig.
4 1a. The shortest distance between any two holes is 5.08 mm. A 1.27 cm insert
5 is machined into each end of the copper bar. The insets are necessary in order
6 that a copper nose and tail may be attached later. The copper bar containing
7 the holes, a copper nose, and a copper tail are etched clean in a nitric acid
8 solution, they are rinsed in water, rinsed a second time in methanol, and are
9 then dried. 19 niobium bars, 2.54 cm in diameter and 61 cm long 2 are wiped
10 clean with acetone and are inserted into the holes in the copper bar 3. The
11 nose and tail are tungsten inert gas (TIG) welded into place, and the billet is
12 evacuated at a temperature of 427°C to a pressure of 10^{-6} torr. The billet is
13 then sealed as shown in Fig. 1b.

14 In preparation for extrusion, the billet is heated at a temperature of
15 816°C for a period of three hours. The billet is then extruded to a diameter of
16 2.54 cm. The extruded rod is cropped to ensure uniformity, and the cropped
17 rod is cold drawn at an areal reduction rate of 20% per die pass to a final
18 hexagonal diameter of 3.48 mm. That is, the final wire shape is hexagonal and
19 the distance from flat to flat across the hexagon is 3.48 mm. At this size, the
20 niobium filament diameter is 0.61 mm.

21 The wire is straightened and cut to 61 cm lengths. Pure copper rod is
22 drawn to 3.48 mm diameter hexagonal wire and is straightened and cut to 61
23 cm lengths in the same manner as the wire containing the Nb filaments. Both
24 types of filaments are cleaned in nitric acid in the same manner as was the
25 primary billet. 1045 of the Nb-containing filaments 4 are stacked in
26 symmetrical fashion.

27 A section of 0.64 mm thick Nb sheet 7, 45.7 cm wide and 610 cm long,
28 is wiped clean with acetone and is inserted circumferentially into a clean
29 copper can 8 having an internal diameter 14.5 cm, an external diameter 16.5
30 cm, and a length of 63.5 cm 7. The sheet 7 overlays by 0.3 cm so as to ensure a

1 continuous layer. The long dimension of the sheet runs along the can length.
2 The stack of filaments is inserted into the niobium-lined can (see Fig. 2) and
3 the copper nose and tail are electron beam welded into place under a vacuum
4 of 10^{-4} torr. The billet is then hot isostatically pressed at a pressure of 104 Mpa
5 and temperature of 650°C for four hours. The isostatically pressed billet is
6 machined to a diameter of 15.3 cm, and the billet is prepared for extrusion by
7 heating for three hours at 816°C. The billet is then extruded to a diameter of
8 2.54 cm.

9 The extruded rod is cropped to ensure uniformity. It is then drawn at
10 an areal reduction rate of 20% per die pass to a diameter of 1.02 mm and
11 twisted. At this wire diameter, the diameter of the Nb filaments is 4.06
12 microns, and the thickness of the niobium sheath is 42.6 microns. The total
13 volume fraction of Nb filaments within the Nb sheath is 34.9%.

14 Thereafter, the Nb outer sheath 7 is perforated by means such as
15 slotted rolls as mentioned previously and the product is leached in
16 $\text{HNO}_3/\text{H}_2\text{O}$ at 100°C for 60 min. to remove the copper separating the Nb
17 filaments. The copper-free mass of Nb filaments is then preferably immersed
18 in a tin bath at 1000°C to allow for maximum fluidity and surface tension of
19 the Sn bath. An inert atmosphere of Argon is used to avoid oxidation.
20 Dipping resident time in the Sn bath should be as short as possible (less than
21 10 sec) to minimize Nb_3Sn formation at this stage and maximize the ductility
22 for further processing; i.e. cabling.

23 EXAMPLE II

24 In Example I, a continuous sheath, as shown in Fig. 2, was employed
25 and at the final size the conductor was mechanically perforated as shown in
26 Figs. 3a and 3b to allow for the removal of the copper matrix by acid leaching
27 followed by liquid tin infiltration at high temperatures. It was also shown
28 that the sheath can be applied separately after the conductor has been
29 fabricated by means of taping Fig. 5, Braiding Fig. 6, or by mechanically
30 confining the conductor into a support structure as shown in Figs. 7, 8 and 9.

1 A simpler and considerably less expensive method has been found
2 which accomplishes the same objective. The sheath is constructed exactly as
3 in Example I except now a narrow opening is left which is parallel to and runs
4 the length of the filaments shown in Fig. 10.

5 The size of the opening can be adjusted to permit rapid copper removal
6 of the matrix by acid leaching and still retain the sheath's ability to constrain
7 and support the filaments. Following the final reduction, twisting and copper
8 removal, a product which is an exact duplicate of the taping example of Fig. 5
9 is remarkably produced. Several variations are possible in the sheath design.
10 For example, more than one opening can be used.

11 The twisting action causes the outer filaments to stretch more than the
12 inner strands and when the copper matrix is removed, the outer filaments are
13 under tension and act to compress and constrain the inner bundle of
14 filaments. It has been observed that untwisted or lightly twisted, the outer
15 filaments will tend to exfoliate at the sheath opening.

16 This conductor was leached in a $\text{HNO}_3/\text{H}_2\text{O}$ 50/50 acid solution at
17 100°C to completely remove the copper matrix. The following Cu-Sn alloys
18 were then used for infiltration experiments:

Cu wt%	Sn wt%
87	13
67	33
50	50
25	75
20	80
10	90
0	100

19 Successful infiltration at 1000°C was obtained for all alloys with the
20 exception of the 13% Sn alloy. This alloy has a liquidus temperature of 1000°C

1 and would have required a temperature of at least 1200°C which was beyond
2 the temperature capability of our small laboratory furnace.

3 The 33% Sn alloy sample was subsequently heat treated at 675°C for 24
4 and 48 hours. Metallographic examination of the cross section for the 48 hour
5 sample reveals a substantial Nb₃Sn reacted layer, averaging 4-6 micron in
6 thickness both in the filaments and in the surrounding sheath.

7 As shown in Fig. 4, a central copper core can be used. As a typical
8 requirement, up to 40% copper is needed to insure stable conductor
9 performance. To prevent Sn contamination of the copper core, a Ta protective
10 barrier is employed in Fig. 4. It should be recognized that this structure by
11 itself contributes a significant amount of support and that together with the
12 external sheath of this invention would combine to protect the fragile Nb₃Sn
13 filaments inside. It has been shown that a high strength copper containing Nb
14 composite has been successfully used in conjunction with Nb₃Sn conductors
15 and can be used in place of pure copper. (See advances in Cryogenic Eng.,
16 Vol. 42, Plenum Press, NY 1996, pages 1423-1432).

17

1 1. A process for manufacturing a Nb₃Sn superconductor comprising
2 the steps of establishing multiple niobium components in a billet of a ductile
3 metal, working the composite billet through a series of reduction steps to
4 form said niobium components into elongated elements, each said element
5 having a thickness on the order of 1 to 25 microns, surrounding said billet
6 with a porous confining layer of an acid resistant metal, immersing said
7 confined billet in an acid to remove said ductile metal from between the
8 niobium elements while the niobium elements remain confined by said
9 porous layer, immersing the confined mass of niobium elements in a liquid
10 metal containing tin to coat said niobium elements with said liquid metal and
11 subsequently reacting said tin with the Nb filaments to form Nb₃Sn.

12 2. The process of claim 1 wherein said reaction is accomplished after
13 said filaments are formed into a magnetic coil.

14 3. The process of claim 1 wherein the liquid metal bath is pure tin.

15 4. The process of claim 1 wherein the liquid metal bath is a copper
16 alloy containing up to 95 wt% Sn.

17 5. The process of claim 1 wherein the liquid metal bath is a copper
18 alloy containing up to 95 wt% Sn and at least 13 wt% Sn.

19 6. A process for manufacturing a niobium-based superconductor
20 selected from the group consisting of Nb₃Sn, Nb₃Al, NbN, and NbC
21 comprising the steps of establishing multiple niobium components in a billet
22 of a ductile metal, working the composite billet through a series of reduction
23 steps to form said niobium components into elongated elements, each said
24 element having a thickness on the order of 1 to 25 microns, surrounding said
25 billet with a porous confining layer of an acid resistant metal, immersing said
26 confined billet in an acid to remove said ductile metal from between the
27 niobium elements while the niobium elements remain confined by said
28 porous layer, exposing the confined mass of niobium elements to a material
29 capable of reacting with Nb to form a superconductor.

30 7. The process of claim 6 wherein said material is nitrogen.

1 8. A process for manufacturing a A-15 or B1 type compound
2 superconductor comprising the steps of establishing multiple primary metal
3 component in a billet of a ductile metal, working the composite billet through
4 a series of reduction steps to form said primary metal components into
5 elongated elements, each said element having a thickness in the order of 1 to
6 25 microns, surrounding said elements with a porous confining layer of an
7 acid resistant metal, immersing said confined elements in an acid to remove
8 said ductile metal from between the primary metal elements while the
9 primary elements remain confined by said porous layer, contacting the
10 confined mass of primary metal elements with a reactant and reacting the
11 primary metal elements with the reactant to form the A-15 or B1
12 superconducting compound.

13 9. The process of claim 1 wherein said billet is surrounded by said
14 porous layer prior to the last reduction step.

15 10. The process of claim 1 wherein said porous layer is created by
16 twisting the reduced billet so that outer elements in the billet serve to confine
17 inner elements in the billet when the ductile metal is removed from the billet.

18 11. The process of claim 1 wherein said porous layer is created by
19 running at least one outer element along the outer surface of the reduced
20 billet and twisting the reduced billet so that outer elements in the billet serve
21 to confine inner elements in the billet when the ductile metal is removed from
22 the billet.

23

1 A niobium-based superconductor is manufactured by establishing
2 multiple niobium components in a billet of a ductile metal, working the
3 composite billet through a series of reduction steps to form the niobium
4 components into elongated elements, each niobium element having a
5 thickness on the order of 1 to 25 microns, surrounding the billet prior to the
6 last reduction step with a porous confining layer of an acid resistant metal,
7 immersing the confined billet in an acid to remove the ductile metal from
8 between the niobium elements while the niobium elements remain confined
9 by said porous layer, exposing the confined mass of niobium elements to a
10 material capable of reacting with Nb to form a superconductor.

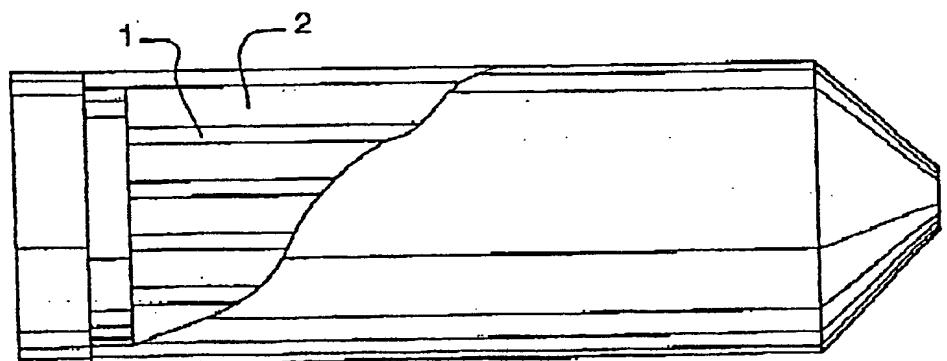
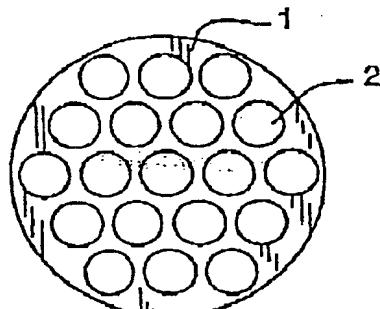


FIG. 1

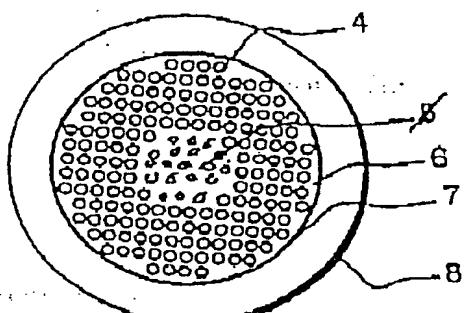


FIG. 2

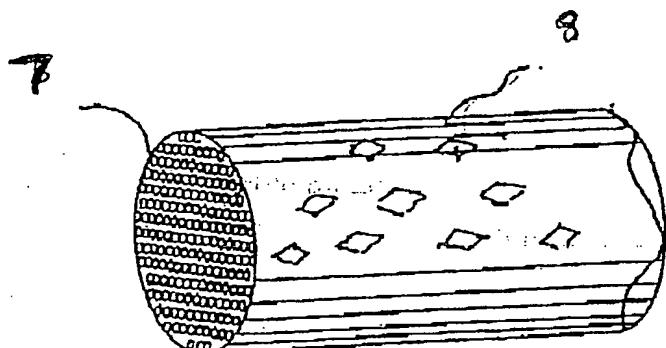


FIG. 3 a

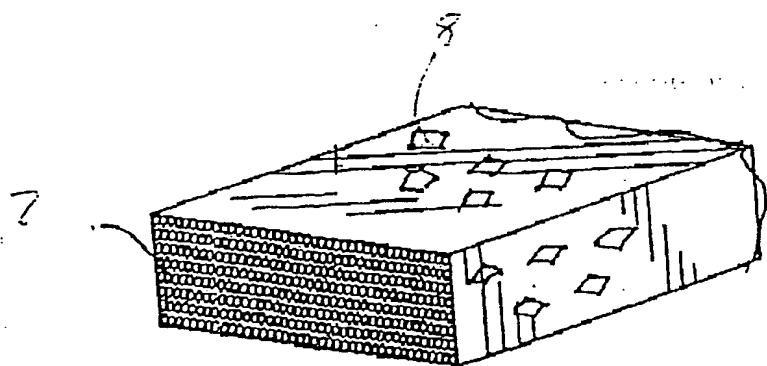
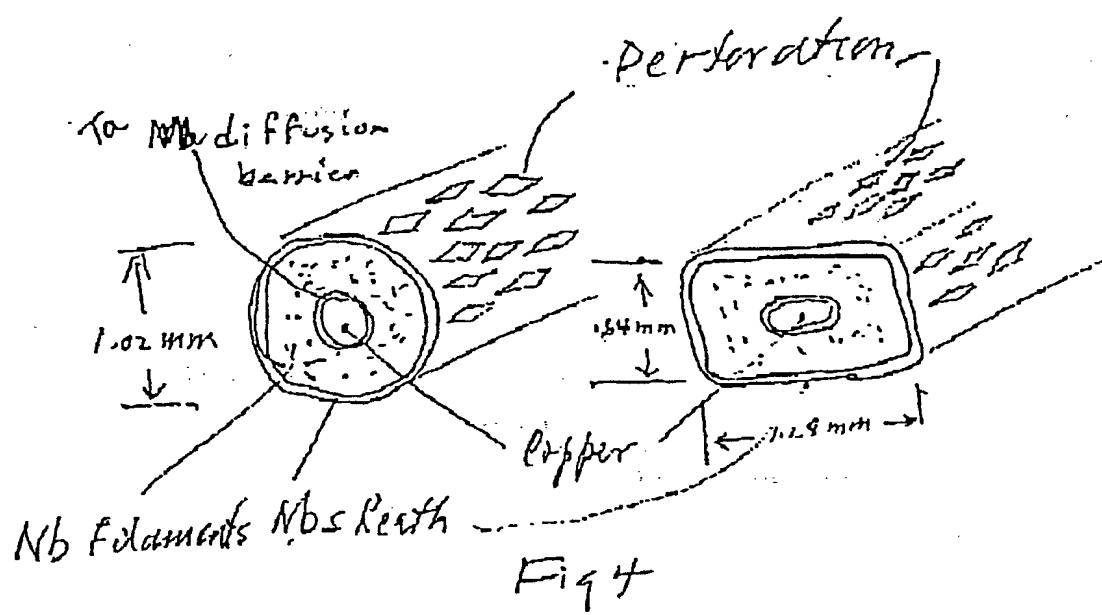


FIG. 3 b



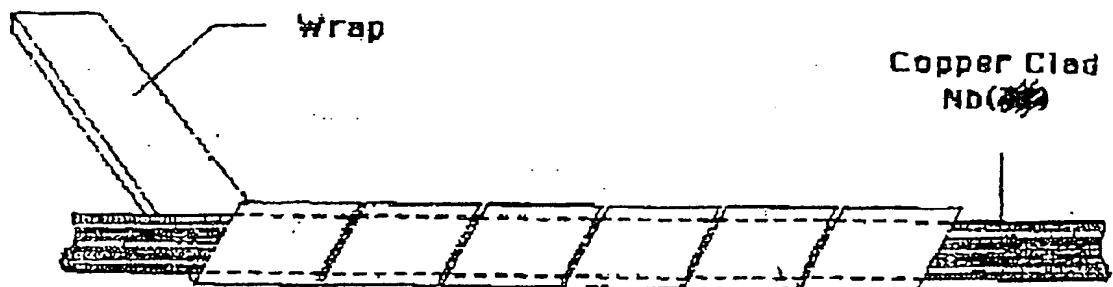


Fig 5

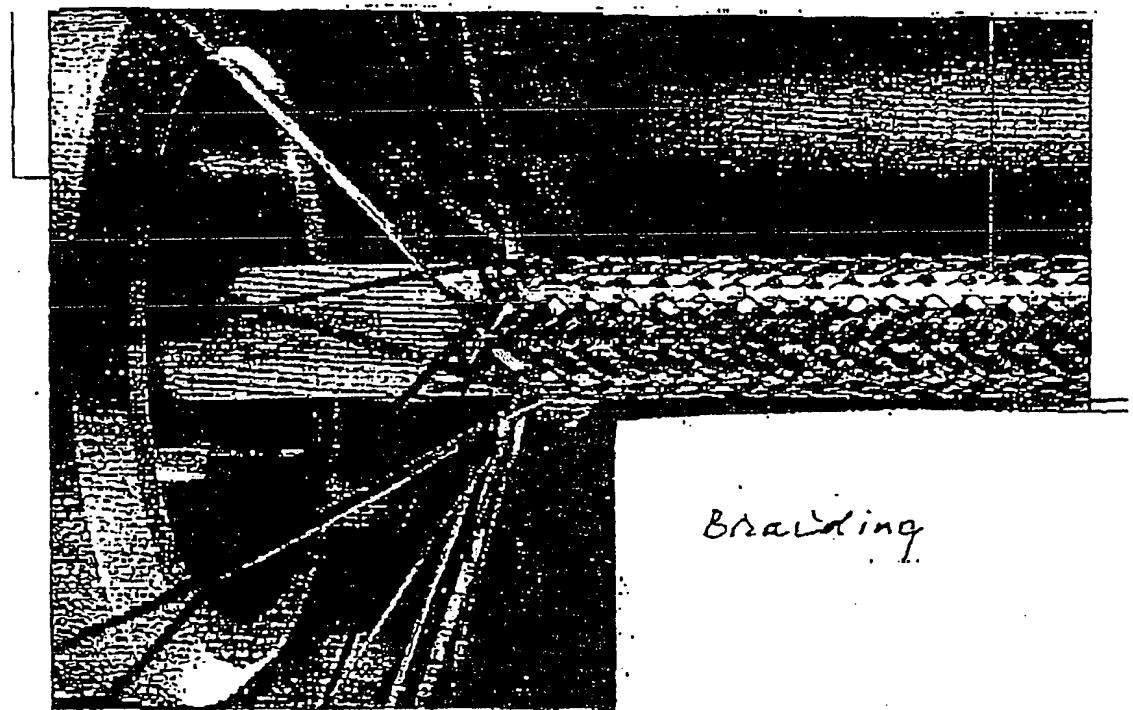


Fig 6

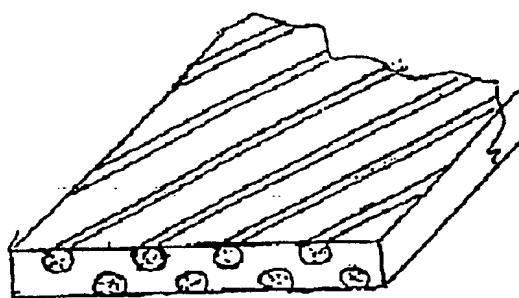


Fig 7

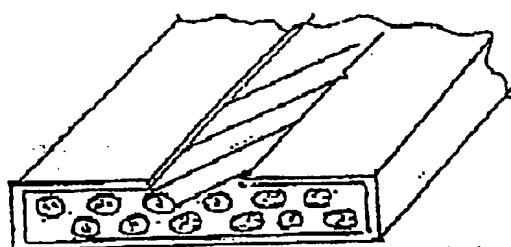


Fig 8



Fig 9

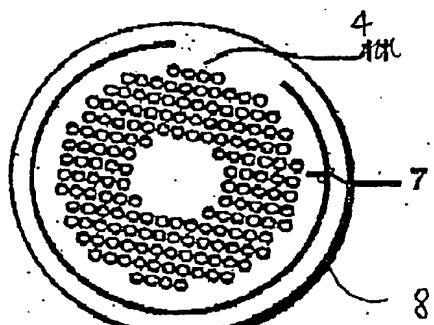


FIG. 10

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(10) International Publication Number
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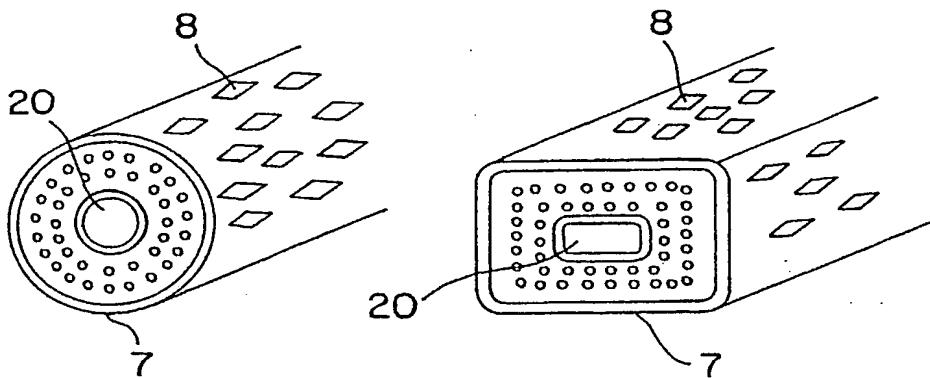
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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: CONSTRAINED FILAMENT NIOBium-BASED SUPERCONDUCTOR COMPOSITE AND PROCESS OF FABRICATION



(57) Abstract: A niobium-based superconductor is manufactured by establishing multiple niobium components in a billet of a ductile metal, working the composite billet through a series of reduction steps to form the niobium components into elongated elements, each niobium element having a thickness on the order of 1 to 25 microns, surrounding the billet prior to the last reduction step with a porous confining layer of an acid resistant metal, immersing the confined billet in an acid to remove the ductile metal from between the niobium elements while the niobium elements remain confined by said porous layer, exposing the confined mass of niobium elements to a material capable of reacting with Nb to form a superconductor.

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A. CLASSIFICATION OF SUBJECT MATTER
 IPC 7 C23C2/00 H01L39/00 H01B12/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 534 219 A (MARANCIK WILLIAM G ET AL) 9 July 1996 (1996-07-09) the whole document ----	1-11
A	US 5 174 831 A (RUDZIAK MARK K ET AL) 29 December 1992 (1992-12-29) the whole document ----	1-11
A	US 5 869 196 A (RUDZIAK MARK K ET AL) 9 February 1999 (1999-02-09) cited in the application the whole document -----	1-11

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 00/10464

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		WO 9828129	A	02-07-1998

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